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EXPOSURE

vol. 5 no. 4 a newsletter for ocean technologists

Moored Temperature And Conductivity Measurements

The Applied Physics Laboratory and the Department of Oceanography at the University of Washington have been making moored temperature measurements since 1969 and moored conductivity measurements since 1972. Temperature is measured by a thermistor-controlled Wien bridge oscillator (see *Exposure*, Vol. 1, No. 1). Accompanying conductivity is measured by either a Plessey Environmental Systems inductive conductivity sensor or a Wien bridge oscillator electrode conductivity sensor. For another application using these Wien bridge oscillator sensors, see *Exposure*, Vol. 3, No. 3. This article describes the equipment used in the measurements and discusses some results of an evaluation of the temperature and conductivity sensors.

EQUIPMENT: The temperature sensor uses a thermistor as a variable resistance input to a Wien bridge oscillator (WBO). The thermistor is pressure-protected and mounted in a tube isolated from the electronics case. The time constant has been increased to 1 minute to make it compatible with the sampling interval by the addition of a Delron mass. The WBO electrode conductivity sensor uses a 3-electrode Beckman cell as the variable resistance input to a WBO in place of the thermistor used in the temperature sensor. A WBO sensor draws 8 mA at 12 V and puts out a 2.5 V sine wave of 6 to 12 kHz corresponding to a temperature of about -2 to 30 degrees Celsius, or a conductivity of about 10 to 60 mmho/cm. The temperature sensor is 5 cm in diameter and 36 cm long, while the conductivity sensor is 5 x 8 cm and 25 cm long. Each sensor weighs about 0.7 kg.

The Plessey Environmental Systems Model 6015 conductivity sensor, which is the inductive sensor used in their 9040 CTD probe, is packaged with its own electronics pressure case. To measure the conductivity, seawater provides an inductive loop that couples two toroidal transformers in the sensing head. A Paraloc amplifier measures the amount of coupling and converts it into an FM signal. The sensor draws 30 mA at 24 V and puts out a 5 V sine wave of 1 to 10 kHz, corresponding to a conduc-

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tivity of about 10 to 40 mmho/cm. The package weighs 8 kg in air, is 9 cm in diameter and 47 cm long. Relative sizes can be seen in Figure 1 which shows all three sensors.

A typical taut mooring (Figure 2) consists of an anchor, acoustic release, Nolaro strength member (a non-twisting Dacron rope with a plastic abrasion jacket), electrical cables taped to the strength member, a 24-inch diameter aluminum sphere (containing all power batteries and recording electronics), and a subsurface float. The sensors (including pressure) are attached to the strength members at the desired positions and electrically connected to the recording capsule by DSS2 cable loosely taped to the strength member (Scotch 33 tape has worked well). This allows great flexibility in building a new array from the pieces of an old one or replacing a bad conductor. Arrays have been constructed as short as 24 m (Figure 2) or as long as 1000 m.

The arrays are deployed anchor last. As the array is paid out, 16-inch diameter Polyform® floats are tied along the array every 100 m to keep the array at the surface. When the anchor is dropped, the array is pulled under and these floats collapse with pressure. For recovery the anchor is released and the subsurface float surfaces and is retrieved and detached. The cable bundle is then run through a 24-inch block and around a capstan. The cable tension can be several hundred pounds and the electrical cable is not damaged by the strength member while going around the block or capstan. The sensors are cut off as they pass by the rail.

The FM signals from the sensors are digitized and recorded in the capsule

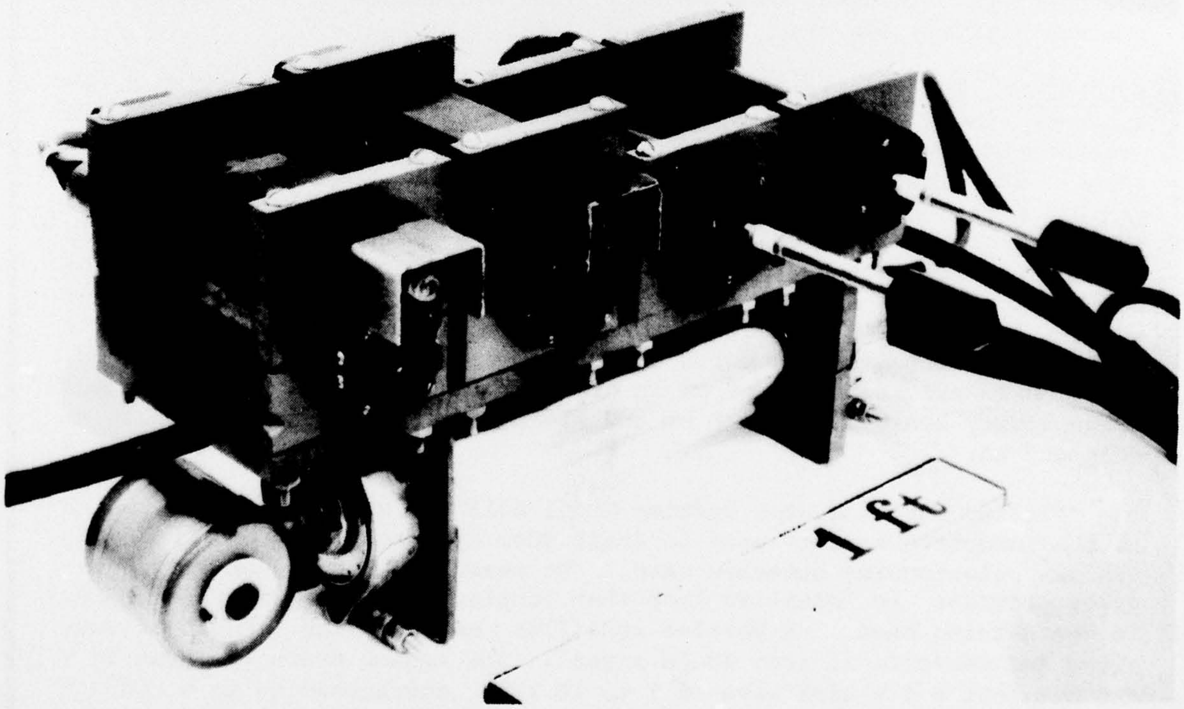


FIGURE 1. A sensor grouping from the test. The inductive sensor is seen on the bottom, the electrode sensors top left, and temperature sensors top right. The array strength member and the electrical cables are seen at the right. The spacing between sensors is 10 cm.

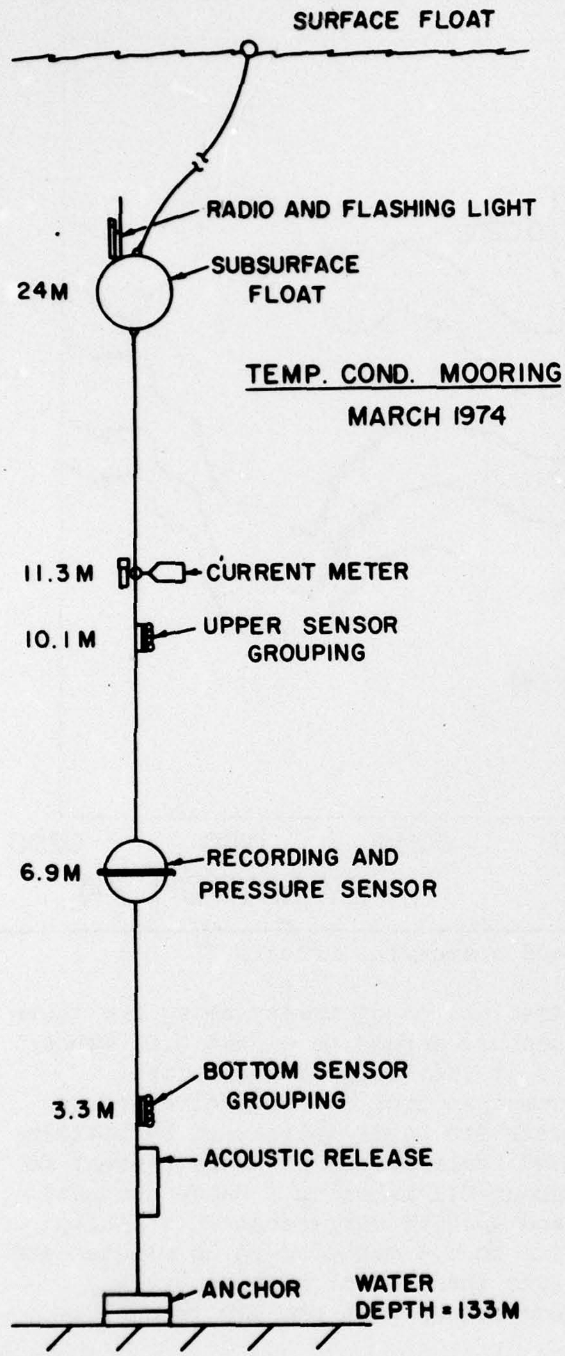


FIGURE 2. The mooring used in the sensor evaluation test. Normally no surface float is used, and sensors are attached individually along the array.

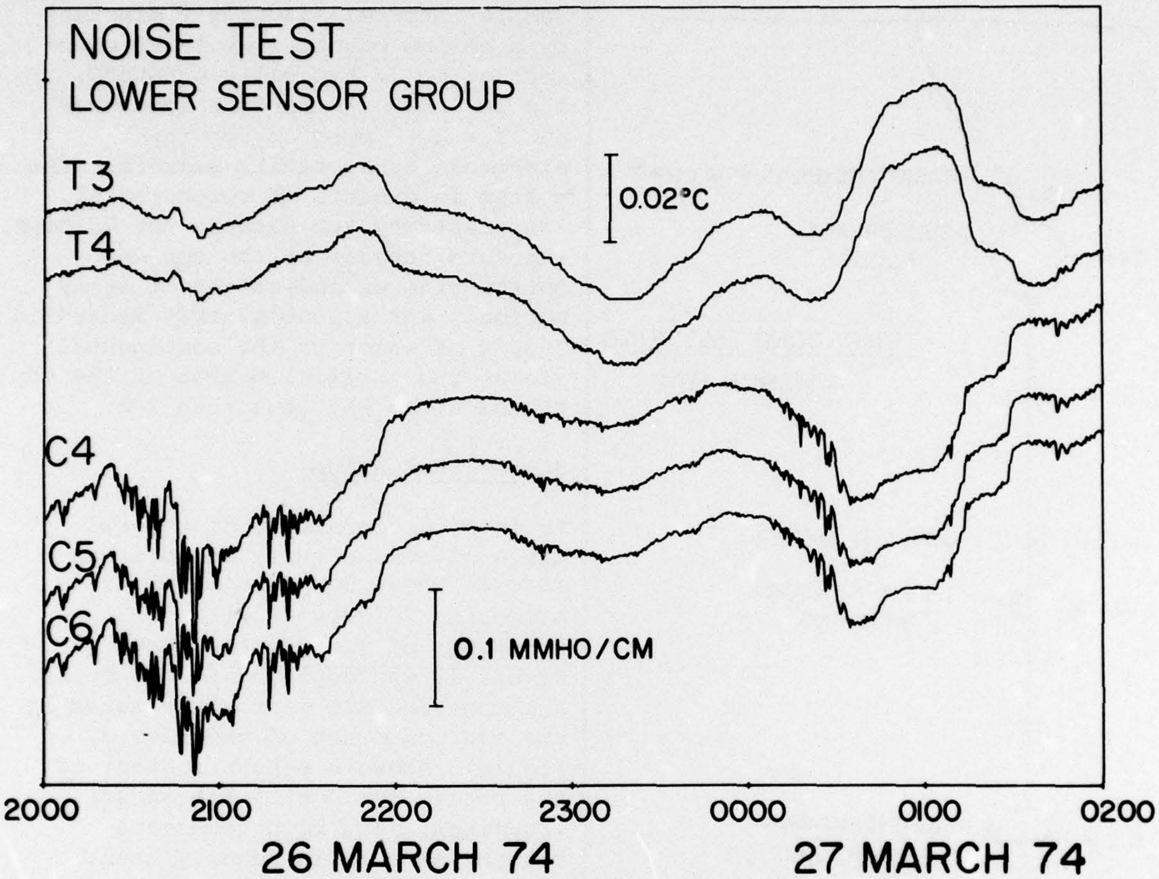
on computer-compatible magnetic tape. The sensors are sampled for one-twelfth of a second during every sample interval (usually 2 minutes) by a period count. The least count resolution is typically 0.0005°C, 1×10^{-4} mmho/cm for the inductive and 1×10^{-3} mmho/cm for the electrode conductivity sensors. The system is capable of recording 11 sensors every two minutes for 40 days. Pressure sensors at the top and bottom give an indication of array motion. For a 1000 m array moored in 1400 m of water on the continental slope, the vertical motion of the top of the array was less than 2 m.

Sensor Evaluation:

An *in situ* comparison of the two types of conductivity sensors was made in Puget Sound in March 1974. A mooring (Figure 2) with two groupings of sensors, as shown in Figure 1, was deployed for 90 hours. Accompanying ST[illegible]sts were taken at the start an[illegible]f the record. Figure 3 sho[illegible] hour segment of the record for one of the sensor groupings. The high coherence between sensors is readily seen.

Temperatures agreed with STD casts to within 0.01°C. The difference between the two temperature records was 0.0018°C (3 least counts), and showed no relative drift during the 90 hour record. The rms variation about this difference was 0.004°C or 1 least count. This implies the spectra are limited by digitizing rather than sensor noise. (For a period count, the digitizing noise is white and spectral density = 1.3 • least count squared • sample interval). This digitizing noise level is about 1 decade below the observed spectral level at 10 cph (typically 2 decades in open ocean regions) and 7 decades below observed spectral level at tidal frequencies. Temperature calibrations since 1970 show linear drifts of typically 4 to

FIGURE 3. A detailed plot of a 6-hour section of data comparing sensors. Ts and T4 are the temperature sensors, C4 is the inductive conductivity sensor, and C5 and C6 are the electrode conductivity sensors.



5 millidegrees C/year. Therefore, these sensors will do an excellent job of measuring the temperature signal in the ocean at frequencies out to the sensor response cutoff (1 minute time constant), where our measurements become limited by the digitizing noise rather than sensor noise.

The conductivity sensors were not so well behaved. The record constructed by taking the difference between two sensor outputs is the sum of the sensor noise and the signal due to imperfect calibration constants. The three difference records plotted in Figure 4 show that the inductive and the electrode sensors have significantly different behavior. A number of causes must be considered, including flushing, electrode fouling, and anemometer effects.

Absolute conductivity among the three sensors agreed to within 0.01 mmhos/cm at the start of the record. Comparison of the inductive sensor with STD casts calibrated by bottles and thermometers showed agreement to about 0.1 mmhos/cm. Large temporal and spatial variations in salinity (up to 0.6 mmhos/cm in 30 minutes and less than 100 m) made accurate comparison with the STD impossible.

Although the inductive and electrode sensors started out within 0.01 mmhos/cm, both electrode sensors showed a decrease in conductivity relative to the inductive sensor, probably due to electrode fouling. Over the 90-hour record the average drift rates were 5×10^{-4} and

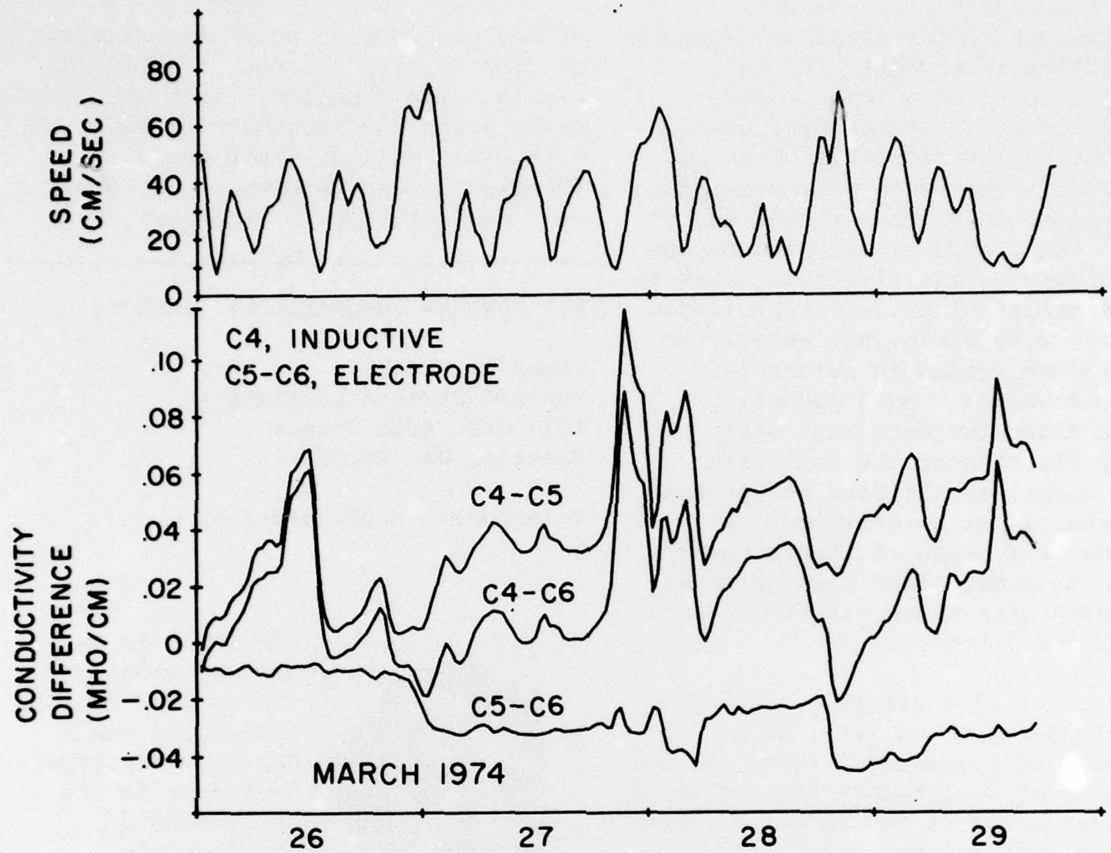


FIGURE 4. The difference records for the three conductivity sensors are shown with a nearby current speed record. The top two conductivity difference curves drift upward showing a decrease in conductivity as measured by the electrode sensors. The large peaks in the difference records are unexplained. The electrode sensor difference is quite flat except for sudden changes at times of high water velocity.

2×10^{-4} mmhos/cm/hour, implying a 0.36 or 0.13 mmho/cm drift in one month, an unacceptably high change.

The difference between the two electrode sensors shows less relative drift. This drift is composed mainly of sudden shifts which occurred at times of high water velocity, perhaps indicating a flushing effect, either cleaning out one sensor, or carrying electrode contamination to the other. The difference record between inductive and electrode sensors is correlated with the current speed. Peaks of increasing conductivity (0.01 to 0.02 mmhos/cm) occur at velocities below 10 cm/sec. When the flow was low for 2 hours near the end of the record, a peak of 0.04 mmhos/cm was observed. This is an instrument effect due to heating of the water in the measurement cell of the inductive sensor, which is also seen in CTD records. From Figure 4 it is clear that this heating and apparent anemometer effect is critical for the inductive sensor and negligible for the electrode sensor, although adequate flushing is important for accurate measurement in both cases.

There are broad peaks in the inductive/electrode difference records which are not directly correlated with the current velocity. These peaks are about 0.1 mmhos/cm and are the major discrepancy which needs to be explained before the inductive sensor can be relied upon for moored measurements.

Calibrations of the electrode sensors show shifts in conductivity of several tenths of a mmho/cm in 6 months time. These may have been in part due to the electrode cleaning procedure. The cells were soaking in hot chromic acid, then rinsed in hot water. Acid crystal trapping in the platinizing on the electrode seems to be a major problem. After prolonged flushing with clean, hot water, the calibration tended to return to previous values. More recently, calibrations indicate that with proper flushing of the cell with clean water, stabilities better than 0.1 mmho/cm can be obtained for periods of a month of intermittent use. It is not clear how continual immersion with clean electrodes will affect the drift rate.

The measure of a sensor's quality is its signal-to-noise ratio as a function of frequency. From this an estimate of uncertainty statistics or confidence limits can be established. For the temperature sensors, the signal-to-noise ratio is greater than 20 dB for frequencies up to 10 cph. For the conductivity sensors, between 0.1 and 60 cph, the signal-to-sensor difference record (an estimate of sensor noise level) spectral level is greater than 10 dB, decreasing from 30 dB at 0.1 cph to 10 dB at 60 cph.

Since the noise spectra decrease with frequency, the noise spectral value of 1 cycle per month can be considered the uncertainty in the absolute value of the measurement. Extrapolating the spectra from the 90 hour results to 1-month periods, one gets an rms uncertainty of 0.02 mmho/cm for the electrode sensors and 0.2 mmho/cm for the inductive sensor. This large value is caused by the few large unexplained peaks and the smaller peaks due to an anemometer effect. At the present time, it appears that the electrode sensors, at best, could give point measurements of conductivity to about 0.1 mmho/cm over a 1-month period. Even then, calibration checks should be made with CTD profiles. This would translate to an uncertainty of about 0.1 ^{o}/oo accuracy in salinity.

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Jim Irish is an oceanographer at the Applied Physics Laboratory and a Research Assistant Professor in the Department of Oceanography, University of Washington. He received his B.S. in Physics from Antioch College in 1967, and Ph.D. from Scripps in 1971. He believes that the marine scientist must understand his instruments, their response functions, and he must be able to optimally deploy them in the field and do the primary data reduction. His experience has included field work on wind generation of waves, deep ocean tides, internal waves, and fine structure. Work on instrumentation includes a microbaragraph for atmospheric pressure above a wave field and evaluation of noise levels in pressure, temperature, and conductivity sensors. He is presently working on high-frequency measurements of temperature and velocity by metal film techniques from APL's Self-Propelled Underwater Research Vehicle, SPURV.

SOME RESPONSE CHARACTERISTICS OF A FLUID-DAMPED MAGNETIC COMPASS TO DYNAMIC AZIMUTH INPUTS

In the course of testing one type of oceanographic direction sensor used in a prototype instrumentation vehicle, an interesting and unexpected aspect of its dynamic behavior was observed. The sensor was a typically optically-encoded magnetic compass which was fully gimballed and oil damped (Figure 1).

Initially, the object of our test was simply to measure the time constant (classically, the time to reach 63 percent of the steady state output) of the sensor. A fixture was arranged such that the sensor was mounted in its normal vertical position and could be physically rotated by hand. In reality, the input is a ramp forcing function with a completion time of a fraction of a second. It is assumed that the completion time for this input is considerably less than the compass time constant such that a step input is closely approximated.

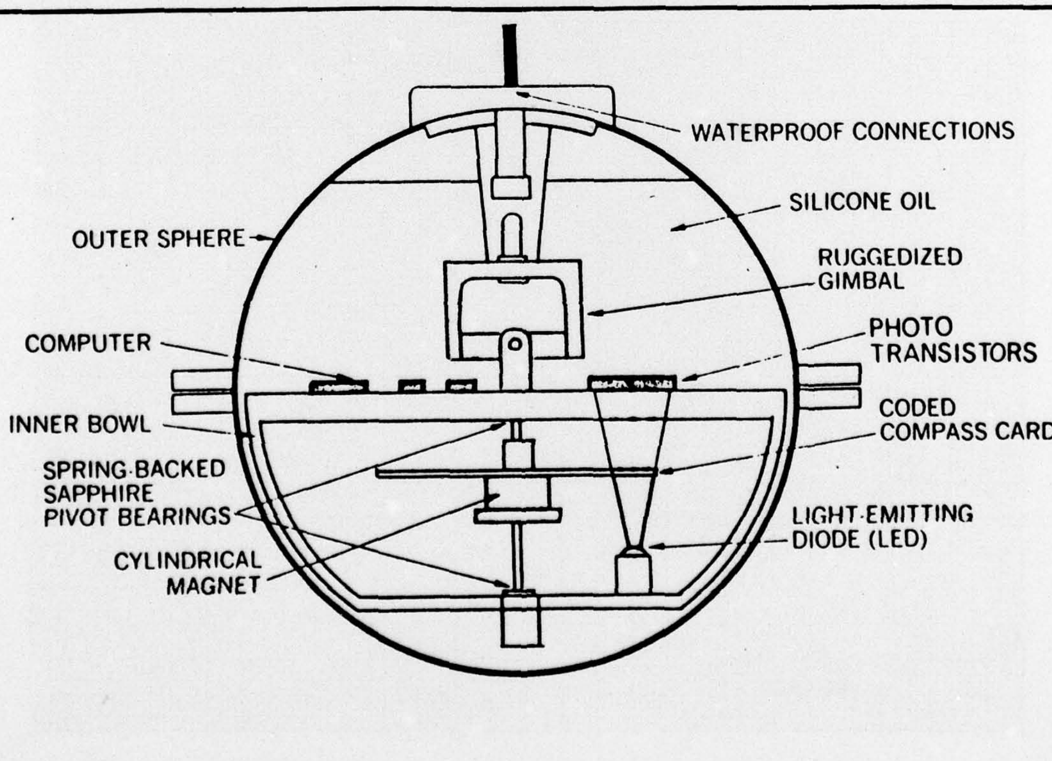


FIGURE 1. Physical Arrangement of a Typical Magnetic-Rotor Direction Sensor.

Rather than the classical critically-damped response of a mass-spring system, the transient behavior of Figure 2 was obtained. The most significant feature of this response is, of course, the large apparent "impulse" that occurs at the initiation of the step angular input. This implies that the sensor has certain peculiar high pass frequency characteristics which are probably non-linear and may be of concern in certain instances. The discrete quantization levels apparent in the step response results, of course, from the digital encoding used in the sensor. An analog output was obtained with a D/A converter buffer stage supplied by the manufacturer.

The characteristics of the transient response were considered and our present explanation for the various driving mechanisms is given in Table 1. Apart from physically modifying the design and mass (inertia) of the compass elements, which was not practical, the only control that could be exerted over the dynamic response characteristics of the compass was through the viscosity and density of the damping fluid. Consequently, the original 8 centistoke viscosity silicone oil was replaced with 1.5 centistoke viscosity oil and comparative step responses were obtained as shown in Figure 3. The initial transient impulses remain unaffected; however, the settling characteristics of the sensor are markedly modified. With 8 centistoke viscosity oil, the sensor has an overdamped settling characteristic as opposed to a slightly underdamped response exhibited with 1.5 centistoke

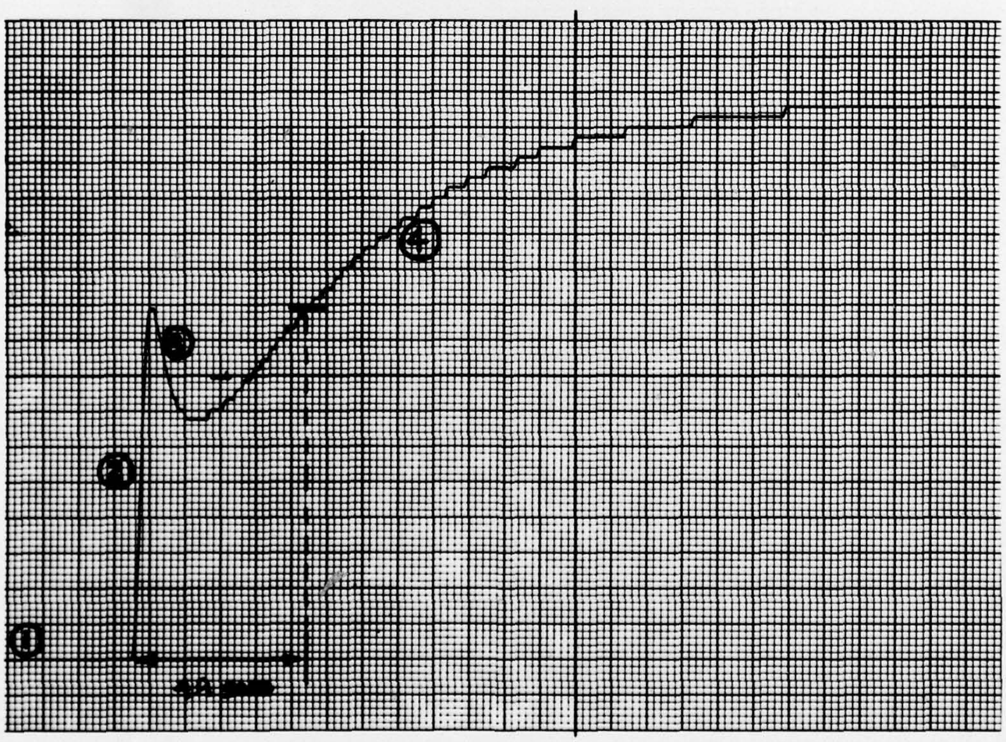
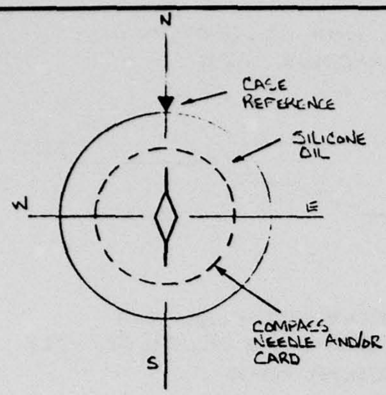


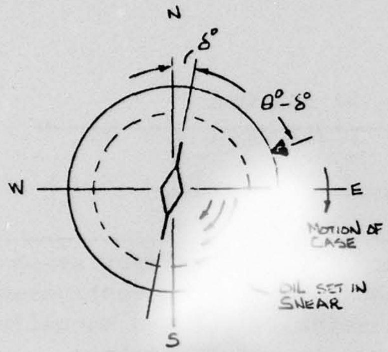
Figure 2. Observed Step Response for the above Direction Sensor (8 Centistoke Viscosity Oil)

TABLE 1.



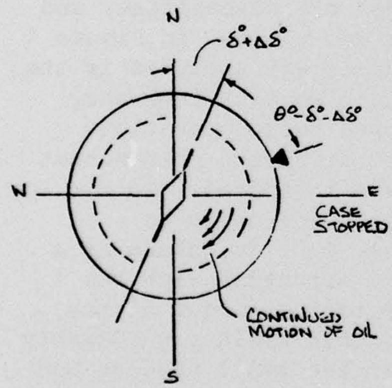
REGION 1

In this reaion, the case reference and needle are aliqned. Since voltaqe out is proportional to the anole between the case reference with respect to the compass needle, voltaqe out is approximately 0 volts at this point; the oil is <u>stationary.</u>



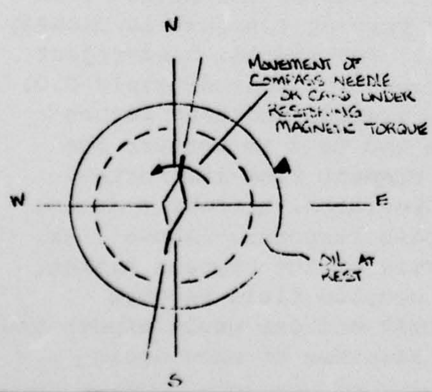
REGION 2

At time = 0+, the case is rotated θ°. As the step input has a finite rise time, the oil underqoes shear such that by the time the step input has been completed, at time = Δt, the inertia of the compass needle has been overcome by the viscous forces of the oil in shear such that it is deflected δ deqrees off of north. Since voltaqe out is proportional to ($\theta^\circ - \delta^\circ$), a larqe output rise in voltaqe occurs rapidly.



REGION 3

At time = $\Delta t+$, althouah the case is stopped the oil continues to shear in the direction of the oriainal rotation because of its own momentum. Viscous forces continue to deflect the compass needle an additional $\Delta\delta$ deqrees off of north. Note that voltaqe out is proportional to ($\theta^\circ - \delta^\circ - \Delta\delta^\circ$) so the voltaqe drops until the oil expends its kinetic eneray.



REGION 4

At time = $\Delta t + \rightarrow \infty$, the motion of the compass needle is reversed under the restoring maanetic torque. The position of the compass needle will oscillate about magnetic north until $\delta \rightarrow 0^\circ$ whereupon voltage out (steady state) will have been obtained.

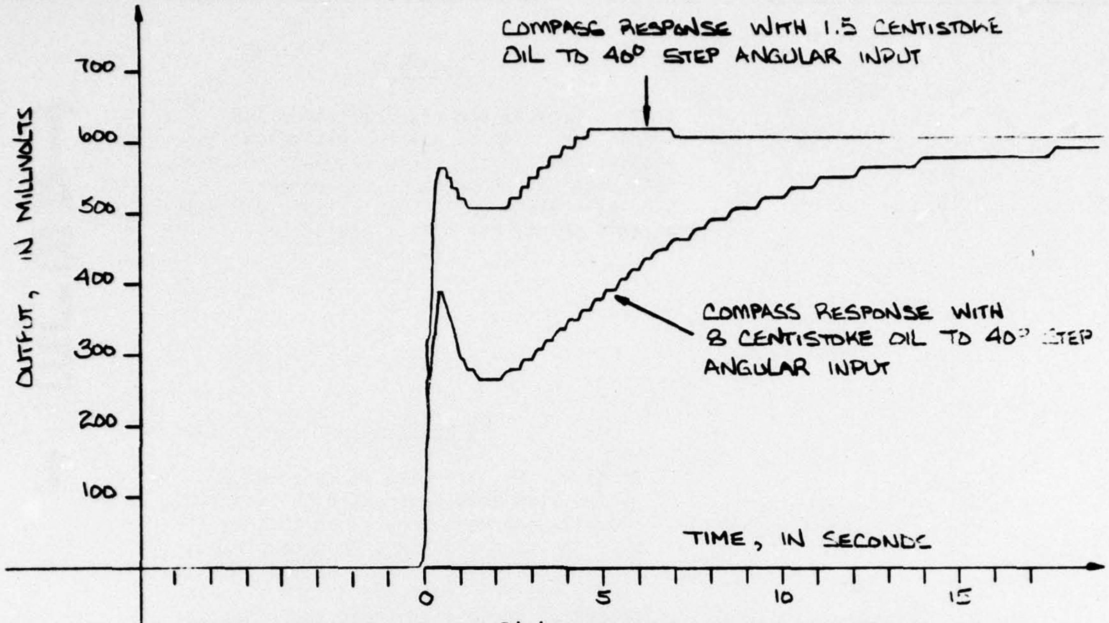


FIGURE 3. Step Response of Digicourse Model 101 Marine Heading Sensor With 1.5 and 8 Centistoke Viscosity Oil.

viscosity oil. Ignoring the initial transient, time constants of about 4 and 0.4 seconds were obtained respectively. The initial transient is a consequence of the viscous and inertial coupling between the compass needle/card and the damping fluid. This is naturally a design compromise; damping is characteristically used to buffer a system from transient, high frequency inputs and to modify its time response; however, the introduction of damping to this particular mass spring system creates non-linear high pass frequency response characteristics.

It can be argued that step inputs are highly unlikely to occur naturally such that responses shown in Figure 2 are not really significant. The most important aspect of a step response, however, is that it characterizes the transfer function of the system from which it was derived. The fact that it points out certain frequency characteristics has significant ramifications to a common class of inputs: sinusoids. For this reason, the frequency domain characteristics of this sensor were also investigated. A quasi-sinusoidal input was manually applied to the sensor at various frequencies. This was done with the two different oil viscosities, and the results are plotted in Figure 4 with the curves extrapolated in the low pass and high pass frequency ranges. Three basic operating regions with differing predominant processes are indicated. In the low pass frequency region, 0 to approximately 0.01 Hz, there is a quasi-static situation with the magnetic restoring torque of the earth's magnetic field considerably greater than the small viscous and inertial forces of the system such that 100 percent response is closely attained. For middle, band-reject frequencies from approximately 0.01 to 1 Hz, viscous and drag forces dominate and tend to perturb the compass element from its north-seeking position, thereby reducing the compass response. Above 1 Hz, the inertia of the compass element and the coupled fluid becomes significant and one would expect the compass response to once again

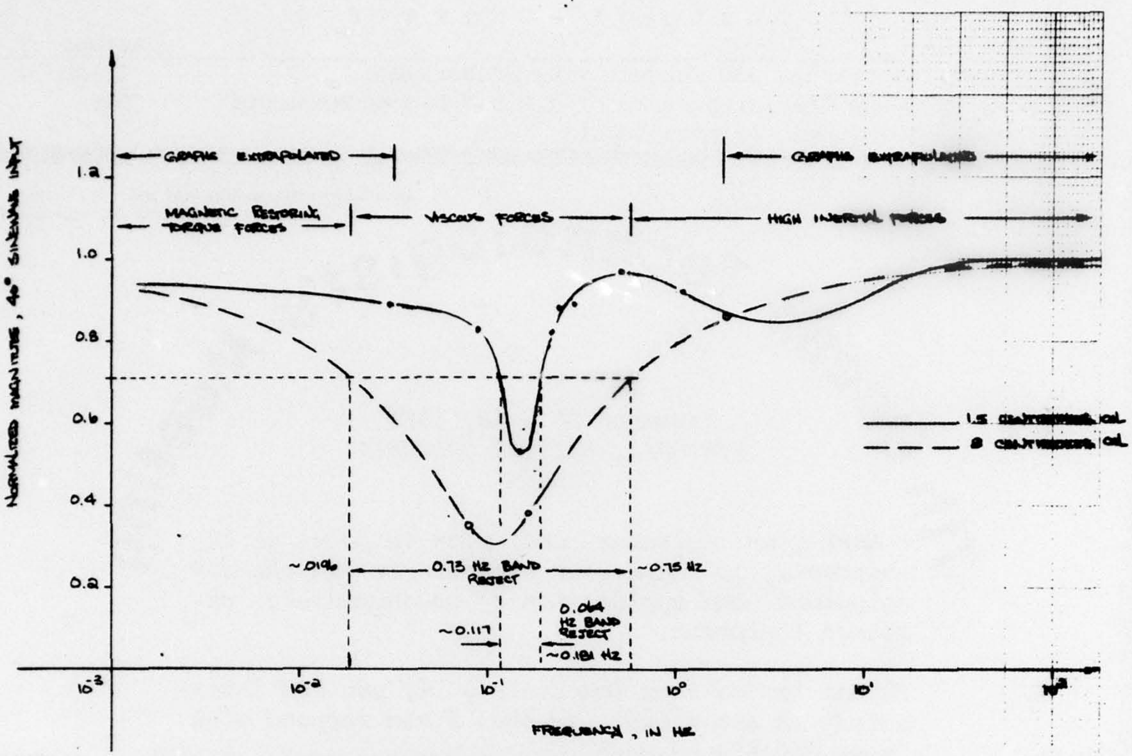


FIGURE 4. Marine Heading Sensor Model 101 Frequency Response For 1.5 and 8 Centistoke Viscosity Oil.

approach 100 percent. The results shown in Figure 4 are quite preliminary and although the apparatus and methods were simple to the point of expediency, the peculiar frequency responses obtained do not appear to be artifacts of the approach taken.

The complex, non-linear nature of the dynamic response of fluid-damped magnetic compasses is sufficiently intriguing and important for further investigation to be worthwhile. Because this class of sensor is commonly used in current meters, floats, buoys, submersibles, boats and other moving "platforms", and have typically been considered as slow response, low frequency devices it is important to appreciate that, beyond this region, high frequency response again develops appreciably. This may pose significant bandwidth and digitization problems for the user, particularly if the anticipated environment is extremely dynamic.

As the Canada Centre for Inland Waters is a water research establishment, neither the resources nor the manpower are available to investigate the transient response of this type of sensor. We hope other researchers will be sufficiently interested to pursue work in this area.

The above article was written by Charles Y. C. Der, who has recently left the Canada Centre for Inland Waters to continue his education.

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Please let me know immediately if you are interested in attending, so that I can respond with more details by mail.

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Rod Mesecar, Editor

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